# David W. Taylor Naval Ship Research and Development Center

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STRAIGHTLINE AND ROTATING ARM CAPTIVE-MODEL EXPERIMENTS TO
INVESTIGATE THE STABILITY AND CONTROL CHARACTERISTICS OF
SUBMARINES AND OTHER SUBMERGED VEHICLES

by

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**19 ABSTRACT (Continue on reverse if necessary and identify by block number)**

This report describes the straightline and rotating arm captive-model experiments that are performed at the David Taylor Research Center to investigate the stability and control characteristics of submarines and other submerged vehicles.

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# STRAIGHTLINE AND ROTATING ARM CAPTIVE-MODEL EXPERIMENTS TO INVESTIGATE THE STABILITY AND CONTROL CHARACTERISTICS OF SUBMARINES AND OTHER SUBMERGED VEHICLES

## INTRODUCTION

The stability and control characteristics of submarines and other submerged vehicles can be determined by performing straightline and rotating arm captive-model experiments at the David Taylor Naval Ship R&D Center (DTNSRDC). From these experiments the hydrodynamic forces and moments are measured and the appropriate stability and control derivatives and hydrodynamic coefficients are determined. This information is used to evaluate the stability and control characteristics of the submarine, and to develop a mathematical model of the vehicle which is then employed in performing computer simulations of the motions of the vehicle.

Vertical and horizontal plane Planar Motion Mechanism (PMM) experiments are performed in the straightline basin (usually Towing Carriage 2) to determine the static ($Z_w'$, $M_w'$, $Y_v'$, and $N_v'$), rotary ($Z_q'$, $M_q'$, $Y_r'$, and $N_r'$), and control derivatives, and the hydrodynamic force and moment coefficients associated with variations in angle of attack, angle of drift, and over and under propulsion. If the vehicle is symmetric (for example, a vehicle with a hull that is a body of revolution, fitted with four identical cruciform stern appendages), then only vertical plane experiments need to be performed.

The hydrodynamic forces and moments are measured over a range of angles of attack (up to about 18 degrees) and sternplane angles in the vertical plane, and over a range of angles of drift and rudder angles in the horizontal plane. In addition, oscillation experiments are performed in the heaving and pitching mode (swaying and yawing in the horizontal plane) at zero speed and underway. By measuring the in-phase and out-of-phase components of the hydrodynamic force and moment the added mass, added moment of inertia, and rotary (effect of angular velocity) derivatives can be determined.

The rotating arm experiments are performed over a range of angles of attack (or angles of drift in the horizontal plane), radii, and sternplane (or rudder angles) in order to derive the nonlinear, coupled hydrodynamic force and moment coefficients. In addition, the rotary (angular velocity) derivatives are measured by performing experiments at relatively large radii, and these measurements are generally more accurate than the corresponding measurements from the straightline oscillation experiments.

## DESCRIPTION OF MODEL, TEST APPARATUS, AND PROCEDURES

The model used for the captive-model experiments is usually 15 to 24 feet in length and approximately 18 to 24 inches in diameter. It is free-flooding and is fitted with a channel located along the axis of the model to be used to attach the force gages to the model. Three force gages are located at the forward strut and three are located at the aft strut to measure the

longitudinal, lateral, and vertical forces. Each assembly is attached to the strut through a gimbal which provides freedom in pitch and yaw. The lateral or vertical forces exerted on the model are experienced as pure reaction forces at each gimbal center, since the moment at the centers is zero and the system is essentially a simply supported beam. The reaction forces are measured by the gages and are equal to the total lateral or vertical force applied to the model. These reaction forces are then resolved with respect to the point that is midway between the gimbal centers to obtain the pitching or yawing moment. The moment is simply the difference in the reaction forces multiplied by half the distance between the gimbal centers. In addition, at one of the struts a gage is connected between the vertical force gage and the strut to measure rolling moment.

Two longitudinally spaced cut-outs in the hull are provided for the two struts to pass through. Provision is made for mounting a motor inside the model to drive the propulsor, and a magnetic pickup and gear tooth are located on the drive shaft to measure the rpm. The control surfaces are either set manually by using stock clamps or remotely using actuator motors and angle transducers.

After each gage is calibrated they are assembled into a forward and aft unit. The gage assemblies are attached to the gage channel inside the model, the propulsion motor is mounted to its support plate inside the model, the propulsor drive shaft is aligned, and the magnetic pickup and gear are positioned inside the model. The model is then ballasted for neutral buoyancy and zero trim using styrofoam.

The A-frame, Planar Motion Mechanism, Stability and Control Instrumentation Penthouse, and model are attached to Towing Carriage 2. The various electrical cables are connected, and polarities are determined for all of the force and moment gages, angle tranducers, and other electrical signals.

The preliminary operations before the experiments can begin include tilting the model several times to remove entrapped air, performing an inclination test to determine the actual difference between the weight and buoyancy of the model, and making several passes down the basin to determine the self-propulsion rpm for the speeds at which the test will be performed.

The rotating arm experiments are performed with essentially the same set up. However, two L-shaped struts are used to tow the model. The two horizontal struts are attached at one end to the gages inside the model and at the other end to the base of the vertical struts which are supported from the rotating arm. The rationale for the L-shaped struts is to minimize any lift induced on the hull from the struts as the model is towed at various radii (pitching angular velocities), angles of attack, and elevator angles. The forces and moments are measured with the same gage system as are the straightline experiments.

Both the straightline and rotating arm experiments are performed at a Reynolds number of about 14 million based on the overall length of the model. For many

years experiments have been performed with various submarine designs to investigate the effect of scaling on the hydrodynamic forces and moments developed on the hull and appendages either at an angle of attack or with the control surfaces deflected to an angle. These experiments have indicated that the hydrodynamic forces and moments vary with Reynolds number. However, there appears to be a Reynolds number above which the hydrodynamic forces and moments no longer significantly change with Reynolds number. Based on comparisons between the results of various captive-model experiments and full-scale trials, if model experiments are performed at Reynolds numbers above about 14 million, then any scale effects between model and full-scale would be negligible for the purposes of making stability and control predictions.

A typical program for the straightline Carriage 2 experiments, which is performed at a Reynolds number of about 14 million, is as follows:

| Type of Test | Angle of Attack/ Drift (deg) | Sternplane/Rudder Angle (deg) |
|---|---|---|
| Static Stability | -18 to 18 | 0 |
| Control | -4 to 4 | -25 to 25 |
| Heaving/Swaying and Pitching/Yawing | 0 | 0 |
| Over-and-Under Propulsion | 0 | -15 and 15 |
| | -18 to 18 | 0 |
| | 0 | 0 |

The oscillation experiments are performed only at standstill, since the rotary derivatives are determined from the rotating arm tests. The frequencies of oscillation are 1.112 and 2.220 radians per second. The over-and-under propulsion experiments are generally performed at a speed corresponding to a Reynolds number of about 8 to 10 million because of the torque limitation of the propulsion motor. The contribution of over-and-under propulsion to the hydrodynamic forces and moments is probably not significantly affected by the reduced Reynolds number. The range of over propulsion rpm's are from self-propulsion to at least twice the self-propulsion rpm. The under propulsion tests are performed to a reverse (backing) rpm about twice the self-propulsion rpm. The longitudinal force is also measured for several rpm's at zero speed.

A typical program for the rotating arm experiments, which is performed at a Reynolds number of about 14 million, is as follows:

| | Nondimensional Pitching (Yawing) Angular Velocity | Angle of Attack (Angle of Drift) (deg) | Sternplane Angle (Rudder Angle) (deg) |
|---|---|---|---|
| four values between | 0.2 and about 0.5 | 0 | 0 |
| | about 0.2 | * | * |
| | about 0.5 | * | * |
| | two other values | * | * |

3

The asterisk indicates that three or four angles are selected which bracket the equilibrium turning condition. These angles, as well as the maximum nondimensional pitching (or yawing) angular velocity, are determined during the tests based on the results of the data.

The standard stability and control nomenclature is used to present the data. An indicator of dynamic stability is the margin of stability G. The value of C can be calculated from the following equations for the vertical and horizontal planes, respectively:

$$G_v = 1 - M_w'(Z_q' + m')/(Z_w'M_q')$$

$$G_h = 1 - N_v'(Y_r' - m')/(Y_v'N_r')$$

A positive value of G indicates stability, and a negative value indicates instability. A value of G close to 1.0 indicates a very high degree of stability, while a value only slightly greater than zero indicates marginal stability. The method for calculating the static derivatives $Z_w'$ and $M_w'$ and the rotary derivatives $Z_q'$ and $M_q'$ are discussed in the references. The nomenclature and equations of motion that are used at DTNSRDC are also provided in these references.

<center>UNCERTAINTY ANALYSIS (U)</center>

INTRODUCTION (U)

(U) In various engineering fields there have been efforts recently to develop a rigorous approach to analyzing the accuracy of experiments. The purpose is to emphasize that all experiments are subject to variations in the relevant physical parameters and their measurement which cannot be controlled by the engineer, and that bounds on the possible variation in reported results should be stated and substantiated.

(U) This approach has been defined as "uncertainty analysis." In uncertainty analysis two contributions to the total uncertainty of results are identified which apply to captive-model stability and control experiments conducted at DTNSRDC. The first type is called bias, and it is the most difficult to quantify. Bias is defined as any effect which is held constant throughout the experiment and which leads to a constant variation of the results from the true value. An example of bias is the error which occurs in calibrating instrumentation. The second type of uncertainty is defined as the precision error, and is the random scatter of results which is seen when experiments are repeated under nominally identical conditions. The relationship between bias and precision errors, and the uncertainty analysis for captive-model stability and control experiments are discussed below.

CAPTIVE-MODEL EXPERIMENTS (U)

(U) It is assumed that both straightline and rotating arm tests are performed,

<center>4</center>

that oscillation experiments are performed to determine added mass and moment of inertia, and that the rotary derivatives are measured on the rotating arm.

(U) Sources of bias errors are found in the following mechanical and electrical equipment used in the experiments: (1) 4-inch block gages (variable reluctance transducers) used to measure the hydrodynamic forces and moments, (2) Hydronautics Multi-T signal conditioners and 6-Hz low-pass filters, (3) Preston 15-bit analog-to-digital converter, (4) Elgar power supply for the signal conditioners, (5) misalignment of the apparatus used to calibrate the 4-inch block gages, (6) misalignment of the gages in the calibration stand, (7) misalignment of the gages in the model, (8) the sensitivity of a gage to forces applied perpendicular to its axis, (9) misalignment of the channel in the model to which the gages are attached, (10) errors in the fabrication of the model, (11) misalignment of the model in attaching it to the towing carriage, (12) constant errors in setting the carriage speed, tilt table angle, control surface angle, and propeller rpm, (13) unknown changes in the water temperature which effects the density and viscosity, (14) currents in the basin, and (15) errors in ballasting the model for neutral buoyancy and trim.

(U) Sources of precision errors include (1) mistakes in setting carriage speed, tilt table angle, control surface angle, and propeller rpm, (2) irregularities in the rails on which the towing carriage travels (the vertical acceleration that is induced causes random errors in the data and effects repeatability), (3) changes in the alignment of the model from test to test, (4) unanticipated unsteady conditions while data are being collected, (5) unknown changes in the water temperature which effects the density and viscosity, (6) unknown water disturbances, and (7) interpretation of data, fairing of curves through the data, determination of slopes, choice of mathematical fit of data, and choice of data to be fitted.

(U) Most of the bias and precision errors are negligible based on observations, tests, and analyses performed over a period of many years. However, the following bias and precision errors can be significant: (1) Changes in gage calibration from time to time probably results in a bias error of about 0.5 percent, (2) fabrication of the appendages for the model, (3) incorrectly setting model test conditions, for example, tilt table angle, speed, propeller rpm, and control surface angles, (4) nonlinearity in the gage calibration probably results in a precision error of about 0.5 percent, (5) irregularities in the rails in the towing basin, and (6) interpretation of the hydrodynamic force and moment data.

(U) Although it is difficult at the present time to quantify all of the individual bias and precision errors, using the submarine stability and control data base, which includes a significant number of experiments which have been repeated, in some cases more than twice, the following overall uncertainty errors may be assigned to the experimental values of the stability and control derivatives for fully appended submarines: (1) static derivatives $Z_w'$, $M_w'$, $Y_v'$, and $N_v'$ between 3 and 5 percent, (2) rotary derivatives $Z_q'$, $M_q'$, $Y_r'$, and $N_r'$ between 7 and 10 percent, and (3) control derivatives between 7 and 10

5

percent.

(U) The accuracy of the experimental derivatives is based upon the repeatability of captive-model experimental results for the same submarine model with similar test procedures and instrumentation performed several months or years apart. This assessment of experimental accuracy includes inaccuracies in the test set-up, instrumentation, and data analysis, as well as environmental variations, and should not be confused with repeatability from run to run during a single test, which typically is much better.

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